World Academy of Science, Engineering and Technology
International Journal of Industrial and Manufacturing Engineering
Vol:6, No:8, 2012

Condition Monitoring in the Management of Maintenance in a Large Scale Precision CNC Machining Manufacturing Facility

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***Abstract*—**The manufacture of large-scale precision aerospace components using CNC requires a highly effective maintenance strategy to ensure that the required accuracy can be achieved over many hours of production. This paper reviews a strategy for a maintenance management system based on Failure Mode Avoidance, which uses advanced techniques and technologies to underpin a predictive maintenance strategy. It is shown how condition monitoring (CM) is important to predict potential failures in high precision machining facilities and achieve intelligent and integrated maintenance management. There are two distinct ways in which CM can be applied. One is to monitor key process parameters and observe trends which may indicate a gradual deterioration of accuracy in the product. The other is the use of CM techniques to monitor high status machine parameters enables trends to be observed which can be corrected before machine failure and downtime occurs.

It is concluded that the key to developing a flexible and intelligent maintenance framework in any precision manufacturing operation is the ability to evaluate reliably and routinely machine tool condition using condition monitoring techniques within a framework of Failure Mode Avoidance.

***Keywords*—**Maintenance, Condition Monitoring, CNC, Machining, Accuracy, Capability, Key Process Parameters, Critical Parameters

I. Introduction

IN the manufacture of large-scale precision items e.g. for aerospace components, using CNC machine tools, a highly effective maintenance strategy is required to ensure that the machines are capable of working to the required accuracy over many hours of productive operation. Central to such a strategy is a maintenance management system which uses advanced techniques and technologies to underpin a predictive maintenance strategy. Condition monitoring (CM) is an important enabler for predicting potential failures in high precision machining facilities [1].

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CM can be applied in two distinct ways, these are:

1. Measurement and analysis of key process parameters that relate to produced part quality such as dimensional stability, accuracy, cycle time and compliance with required tolerances.
2. Observation, measurement and analysis of high status machine parameters such as motor current, structural vibration, ambient temperature, oil cleanliness, that can provide predictive maintenance and thereby potentially avoid machine downtime through failures.

Both of these are fundamental to the 'Failure Mode Avoidance' paradigm [2] which aims to identify and take steps to avoid 'failures' in the 'Design' and 'Manufacture' domains rather than in the 'user' (or 'customer') domain, thereby avoiding the excessive costs associated with the appearance of 'out of specification" product after manufacture. The 'Failure Mode Avoidance' methodology is being developed in the Automotive Industry, where it is used with increasing effect to shorten the time taken, and reduce costs in new product introduction. In the manufacturing environment, the 'Design" stage is represented by the design of the manufacturing system including the process plan, the process equipment, and the maintenance management.

The difference between the two distinct ways in which CM can be applied is that in monitoring key parameters, trends may be observed which may indicate a gradual deterioration of accuracy in the product which may be arrested by appropriate maintenance intervention, whereas in the monitoring of high status machine parameters, trends may be observed which, if not corrected, may lead to machine failure and downtime.

In a previous paper from the Authors' institutions [3] maintenance management strategies for large scale precision machining using CNC machine tools were found to use tool wear and spindle bearing monitoring, but did not base maintenance strategies on monitoring key process parameters. Produced components were found to be routinely inspected and measured, but the causal link between an 'out-of-specification' product and the machine maintenance could not easily be identified. In many cases the maintenance management of individual machine tools was found to be extremely good although in some cases it was observed that a substantial (and costly) maintenance intervention might be initiated as part of a planned maintenance program without clear evidence of faults. In comparison, it is very clear that monitoring high status machine parameters can very effectively indicate the link between cause and effect and so initiate maintenance intervention knowing exactly when it is required and what to look for.

This paper presents examples of both applications of condition monitoring and how they can be used effectively in maintenance management in a precision manufacturing system. In the first application, key machine tool and environmental parameters are monitored and compared with accuracy measurements carried out over the same time period. Trends in the process capability (Cpk defined by the measured accuracy vs. set tolerances) are then used to indicate which maintenance actions are required, and when to bring the process capability back to the required status. In comparison, in the second application, oil analysis is used to indicate how machine downtime can be avoided by predictive maintenance. The paper shows how these approaches to condition monitoring can be used to make intelligent decisions about maintenance management in a precision manufacturing system. Conclusions are drawn about the benefits which could be gained in large scale precision manufacturing.

II. Maintenance Management & Process Capability in Aerospace Manufacturing

BAE Systems is one of the world's leading aerospace manufacturers. Its Samlesbury site houses a high technology machining facility which produces high accuracy and high value titanium and carbon composite components using a range of advanced manufacturing processes. In order to continue to manufacture components to the specified tolerances, the Company must have an effective and efficient maintenance management system to ensure that their manufacturing facilities remain capable for the ever-increasing product complexity. Unplanned machine breakdowns can cause major disruptions to production schedules and lengthy downtimes all of which impact the Company financially. With production time being paramount, the Company has to ensure that maintenance actions are implemented effectively and timed appropriately. Using a predictive maintenance strategy allows maintenance intervention only when necessary, eliminating unnecessary downtime and maximizing availability. A highly effective facility is dependent on maintenance interventions which not only provide a repair for the problem in hand but provide a long term solution which addresses the root causes of failure. Thus the Company can gain experience in fault diagnosis and can continuously improve its routine maintenance performance [4]. By performing regular 'health checks' on machines and recording results, trends can be identified over time, allowing the Company to initiate maintenance interventions before a possible breakdown. This 'Failure Mode Avoidance' strategy would allow BAE Systems to increase its manufacturing efficiency for example by moving production to another machine or ordering spare parts earlier.

Some faults can be very difficult to detect before they become apparent and this results in a 'reactive mode' response, e.g. automatic tool change systems, loading systems, software faults etc [5]. Other faults which influence the accuracy of the machine can however be identified early on using condition monitoring techniques to verify a machine's performance. These results can be recorded and monitored allowing maintenance to intervene only when necessary.

Process capability is very important within any manufacturing industry as it provides a baseline reference for the achievable process accuracy. Process capability is made up of the individual capabilities of all machines and associated process equipment and steps leading up to the manufacture of a finished component [6]. Machine capability is usually defined by the machine manufacturer at the time of purchasing and installation. The Company manufactures components with extremely tight tolerances so it is vital that machines are capable of manufacturing components within this specification. Over time, the capability of a specific machine may decrease because of a variety of reasons such as wear and deterioration so it is very important to assess machine capability at fixed intervals. Other key parts of the whole process should also be monitored regularly, identifying where variations to the finished product can occur prior to the machining process. Mapping a process from start to finish builds up knowledge and enables critical issues to be identified and controlled. If a manufactured part is found to be out of specification this constitutes a failure and the temptation might be to ask for maintenance to 'repair' the machine. Without knowing the root cause of the failure it can be extremely difficult to identify any problems with the machine. Often a tentative adjustment might be made after which the machine would be handed back over to the operators and run again to confirm the effectiveness of the 'repair'. In reality though, it might be found that the manufactured part was found to be out of specification because the machine capability was out of specification. Continuous assessment of process capability including machine capability would therefore allow the link between maintenance effectiveness and process conformance to be seen clearly, and would also give a prediction of the degree of out-of-specification to be expected.

A method to evaluate regularly the condition of advanced CNC machine tools within the Company is the measurement of the volumetric accuracy using the Renishaw Ballbar system. This uses a linear variable differential transformer (LVDT) to measure a machine's ability to trace a circle in the XY plane, and semi-circles in the YZ and XZ planes [7]. Estimates of error can then be calculated in a 3 axis system; although the only direct measurement being made is the radius of the path, the system is able to analyze the trace and calculate many different types of error such as linearity, squareness, scaling, and servo mismatch. During extensive testing at the Company, this method has demonstrated high levels of repeatability and reproducibility. Results from the tests have been analyzed to indicate any deterioration in the machine's spatial accuracy.

III. Monitoring of Key Process Parameters & High Status Parameters

To understand the relationship between maintenance and capability, key process parameters must be identified and monitored over time to determine maintenance effectiveness in terms of the steps required to improve the capability of a machine tool.

Key process parameters are being monitored over time using data logging devices placed in and around the machine tool. The Ballbar system is being used as the measurement device to obtain data from monitoring the machine's spatial accuracy performance. Once a complete data set has been obtained, analysis will begin to correlate the accuracy performance of the machine with the results obtained from the devices used to monitor these key process parameters.

By monitoring some parameters such as ambient temperature and humidity continuously, links can also be made with machine accuracy. This should allow the Company to identify the influencing parameters and take appropriate action. If, for example, the temperature drops significantly at set times during the day perhaps because of the doors being opened, and results from the Ballbar system show a drop in machine spatial accuracy, this knowledge that variations in ambient temperature can reduce machine accuracy performance enables the Company to take action to keep the temperature constant.

High status parameters are parameters directly related to the machine such as oil condition. Unlike key process parameters, they are not monitored continuously; instead they are monitored periodically to check the status of the parameter at a particular time. In this study oil samples were taken from the machine's oil systems (hydraulic, lubrication, hydrostatic), and checked. Oil analysis identifies if there is any contamination or wear debris in the oil and compares it to the baseline specification of unused oil, and any differences between the two are highlighted. By performing a full oil analysis the machine oil condition can be assessed and if satisfactory the study can continue in the knowledge that oil condition can be eliminated as an influencing factor. However, if the oil condition raised a concern such as a high level of debris in the oil, this would directly link with a maintenance action to identify wear in system components. High status parameters such as oil condition can act as a direct indicator of machine accuracy and a maintenance strategy which ensures that periodic checks are in place helps to keep manufactured parts within specification.

By distinguishing between the two types of parameters the Company can identify possible fault causes. The link between maintenance and capability as an out of specification indicator does not always require maintenance interventions.

IV. Variations When Investigating the Entire Process

Monitoring parameters directly related to machine capability such as structural vibrations, enclosure temperature, and local humidity, the capability of the machine tool can be determined from correlation with Ballbar data. If after checking machine capability and high status parameters these factors can be eliminated for the cause of out of specification products, instead it may raise concerns about the entire process. Manufacturing of a single part may contain a series of complex processes in different stages of its manufacture, and because of this it may be possible that a part already contains defects even before it goes through the machining process. It is therefore important to understand the whole process, from the stock material to the end product.

Even the simplest of processes can bring a variety of possible variations which can influence the overall specification of a part. Using the process shown in figure 1 as an example and breaking it down into individual steps, the possible variations can be identified.

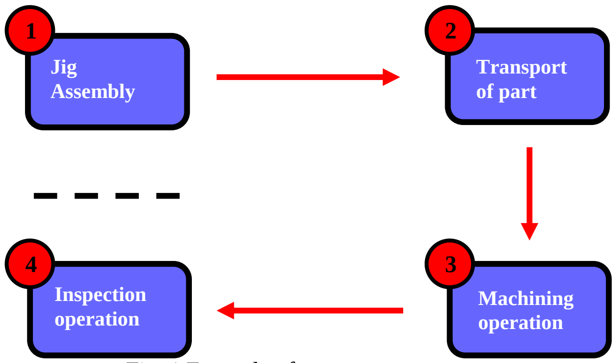

Fig. 1 Example of a process sequence

When parts are mounted on a fixture, obvious variations such as assembly errors can be rectified, however less obvious factors such as the condition of the fixture may not be as easy to identify. Using the fixture as an example, a variety of factors need to be considered such as the last calibration/test date, condition of the fixture, and how ambient temperature affects the fixture dimensions. The fixture may also sustain damage during transportation which again may alter its dimensional properties therefore affecting the accuracy of the part once it moves into the machining operation. It is therefore very important to investigate the whole process determining the key areas for variation and putting in place counter measures to improve the capability of the whole process. By rectifying only machining parameters including high status parameters and not the whole process, parts may continue to be produced out of specification it is therefore imperative to identify critical cause for variation prior to a process.

V. Conclusions

An effective operational link between process or machine capability and maintenance remain vital in the aerospace manufacturing industry to inform effective maintenance management. A successful maintenance strategy relies on efficiency and effectiveness, which can only be achieved by targeting the root cause of failure. To avoid unnecessary downtime, maintenance interventions must be arranged to take place before failure occurs, as part of a 'Failure Mode Avoidance' approach. This approach allows confidence to be built up in the machine so that performance indicators such as capability are considered before initiating maintenance interventions. Out-of-specification parts can occur at any stage of manufacturing process whether this is prior to the machining process or the machining process itself. By distinguishing between key process parameters and high status parameters machine condition can be determined so that if variations occur in these parameters they can be easily identified and correlated with the machine's spatial accuracy performance proving which factors affect the capability of the machine to manufacture to the set tolerances.

The key to developing a flexible and intelligent maintenance framework in any precision manufacturing operation is the ability to evaluate reliably and routinely machine tool condition using condition monitoring techniques such as the Ballbar to assess key process parameters, and to monitor high status machine parameters such as oil analysis. This capability is essential in driving progress towards an intelligent and pro-active maintenance operation. Moving to an intelligent preventative maintenance framework requires considerable investment in both technology and staff to ensure that the tools and expertise are available.

ACKNOWLEDGMENT

The authors wish to thank the Directors of BAE Systems plc. for permission to publish this paper. The work presented here is supported by the Technology Strategy Board through its Knowledge Transfer Partnership programme.

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